STABILITY INFERENCES FROM PRECISION RAWINS

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ABSTRACT

A series of rawins, tracked by an M-33 radar, was carried out at Palestine, Texas, in November 1965. Ascent rates of about 60 m./min. and recording of balloon coordinates at half-minute intervals were used to give fine resolution. In addition to horizontal winds, the flights were analyzed for the vertical wind component, and ascent-rate of the balloon.

The results suggest that some inferences as to thermal structure in the surface layer can be drawn from precision balloon tracking. A uniform rate of ascent is associated with inversion conditions. An ascent that shows two rates, a faster one through the first few hundred meters and a slower one above, occurs when the surface layer is undergoing mixing of either convective or mechanical origin. Attempts to fit an expression of the form

$$V_1/V_2=(z_1/z_2)^p$$

to the profile of wind speed in the surface-based layer agreed moderately well with the expectation of $p\leqq 1/7$ for unstable layers and $p\geqq 1/3$ for inversions. This somewhat weak indication was often supported by the profile of wind direction—uniform direction or slight backing through the mixed layer with rapid veering above. During ascent through unstable layers maximum vertical wind components generally exceeded 0.8 m./sec.; through stable layers they generally subceeded 0.3 m./sec.

1. INTRODUCTION

There are many direct methods of measuring temperature profiles. For the lowest few hundred feet, sensors can be mounted on a tower. For layers a few thousand feet thick, a tethered balloon may be used to raise and lower an instrument package. For deeper layers, radiosondes and rocketsondes are used. Consequently there is no need to use indirect methods to obtain temperature profiles.

Occasionally, however, there are programs involving precise balloon tracking without specific attempts to measure temperatures aloft. The purpose of this paper is to show that useful inferences as to thermal structure can often be drawn from such data. Specifically the work described herein suggests that there are associations between stability and the ascent rate of the balloon, the profiles of wind speed and direction, and the magnitude of the vertical wind component.

The association of stability with the wind speed profile is well known. Above the first few meters the power law

$$V_1/V_2=(z_1/z_2)^p, \tag{1}$$

where V_i is the wind speed at height, z_i, describes the wind profile fairly accurately. Near the ground p is dependent on surface roughness and lapse rate, but above about a hundred meters the influence of surface roughness is negligible. Since most of the published data refer to the layer within which surface roughness is important, there is a lack of agreement on the values of p that are typical for inversions and adiabatic lapse rates.

Sutton [11] gives the physical reasons why, of necessity, $0<p<1$. The one-seventh-power law, $p=1/7$, has been widely used in engineering problems for the non-inversion case. At one time Smith and Singer [10] were apparently recommending $p=1/7$ for lapse and $p=1/3$ to $1/2$ for inversions. Recently, however, the same group [9] favored $p=1/4$ for isothermal and lapse and $p=1/2$ for inversions.

Using a tethered balloon for the layer 5 to 400 ft. Frost found $p=1/7$ for strong lapse, and gave values of $1/4$ and $1/3$ for the neutral and inversion cases. Sutton [11] reported that after extending the work to 1000 ft., Frost later concluded that $p=1/7$ was valid through the latter depth for an adiabatic lapse rate.

Demarrais [2] summarized values of p observed between 11 and 125 m. at Brookhaven and compared his results with many other studies. He found that surface roughness effects were noticeable within the layer studied at Brookhaven. His summary of the work of others emphasized that, if there is a consensus, it is simply that p increases with increasing stability.

Since the rawins that form the basis of this paper were taken at Palestine, Texas, there is special interest in the winds and temperatures observed on a 1,400-ft. tower near Dallas. Izumi and Barad [5], Izumi [4], Thuillier and Lappe [12] and Izumi and Brown [6] have all presented data from the latter installation. The Thuillier and Lappe study, based on 274 profiles, does not attempt to estimate

p but does show evidence of increasing p with increasing stability. All four reports illustrate the frequent occurrence of a low-level jet with surface-based inversions.

The association of stability with wind direction has not been studied intensively. However one can easily deduce what to expect. In a well-mixed layer both momentum and potential temperature will be uniform. Thus an adiabatic lapse rate should be associated with uniform wind direction through the layer. Conversely, with an inversion, which is a manifestation of reduced mixing, wind direction is likely to veer with height as it approaches the direction of the geostrophic wind.

Concerning the association between stability and vertical wind components, studies of smoke plumes have demonstrated graphically that laminar flow is a consequence of inversions. Moreover the characteristic looping of plumes, described by Church [1], illustrates the large vertical components that result from great instability.

There have been few attempts to relate the rate of rise of a balloon to stability. Recently, however, Reynolds [7] reported on such a study at Holloman Air Force Base, New Mexico. He considered effects, between 10,000 and 100,000 ft., on balloons inflated to rise at 850 ft. min.$^{-1}$ He concluded that only 9 percent of the observed variation in ascent rate could be attributed to changes in lapse rate.

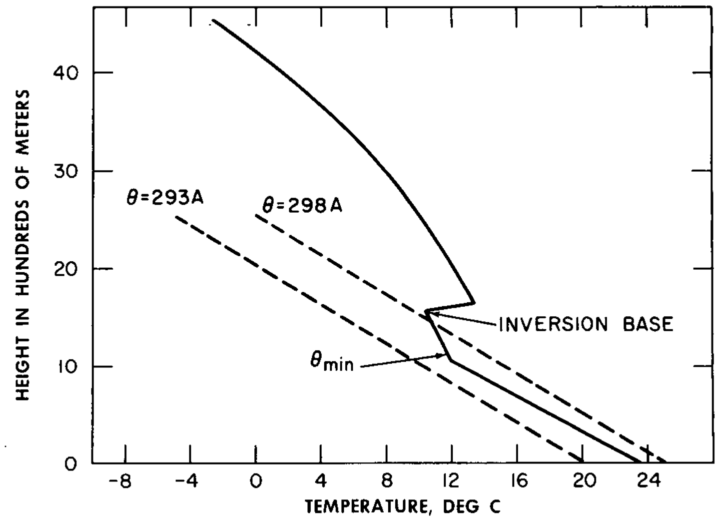

FIGURE 1.—Typical afternoon temperature sounding at Palestine, Texas, in November 1965. Dry adiabatic lapse rate is indicated by dotted lines of equal potential temperature θ.

2. SOURCE AND TREATMENT OF THE DATA

A series of 49 rawins, tracked by an M-33 radar, was carried out at Palestine, Texas, in November 1965. Aluminum foil was tied below 100-gm. balloons inflated to rise at rates ranging from 60 to 200 m. min.$^{-1}$ Azimuth and elevation angles, and slant range were read from dials and transcribed at half-minute intervals. Ten afternoon flights differed in that the balloon train also included a radiosonde and used a larger balloon.

For these 10 flights the thermal structure is known. For the remaining 39 flights thermal structure of the surface layer must be inferred from time of day, sky condition, and wind speed or the radiosonde at Fort Worth 120 mi. away. Given clear skies and light winds, surface-based inversions usually develop within an hour after sunset and persist for 1 to 2 hours after sunrise. Data from the 1,400-ft. tower near Dallas [4, 5, 6, 12] suggest that the inversion climatology of east Texas follows this pattern reasonably well.

Figure 1 shows the typical afternoon temperature profile. Each of the 10 soundings featured a positive lapse rate at the surface with a relatively low-level inversion aloft. The height of the minimum potential temperature, θ_{min}, varied from the surface to the base of the inversion. The presence of, and depth of the surface-based, superadiabatic layer may therefore be implied by specifying the height of the minimum potential temperature.

Rawin data were analyzed by computer. The 2-min. interval centered on each read-out time was used in computing height, rate of ascent, horizontal wind, and vertical wind. Some smoothing results from this procedure. The vertical wind component was computed by subtracting the average ascent rate for the entire flight from the ascent rate corresponding to a particular time in the flight. This procedure assumes that the average ascent rate for the entire flight is a good estimate of the still-air rate of ascent. Since this assumption is somewhat crude, the estimates of vertical wind are equally inexact.

The computer printouts were used to plot balloon height versus time and profiles of wind speed and direction versus height. In the latter profiles, by using a logarithmic scale for height, it was possible to show, as straight lines, the shape of the profiles for $p=1/7$ and $p=1/3$. In the introduction it was pointed out that there was no clear consensus relating a particular value of p to a particular thermal structure. However, the inclusion of the $p=1/7$ and $1/3$ profiles on the graphs permits immediate detection of significant changes in the shape of the wind speed profile.

For the wind direction profiles a kind of normalizing procedure was used to emphasize common features. The first observed wind direction after balloon launch was subtracted from all subsequent wind directions in order to give a profile of the accumulated change in wind direction. With this procedure the first observed wind is always plotted as zero degrees; positive values correspond to veering and negative values to backing.

3. THE RESULTS AND THEIR INTERPRETATION

BALLOON ASCENT RATE

Figures 2, 3, and 4 illustrate the same idea. Each of them compares a balloon ascent during the afternoon with an ascent during a presumed surface inversion on the same day. In figure 2, the ascent at 1419 LST occurred with about $\frac{5}{10}$ cloud at 3,000 ft. and thin broken cirrus above. The radiosonde gave the height of θ_{min} as 1075 m. and the base of the inversion aloft as 1525 m. The ascent rate was uniformly slower above 1600 m. than in the lower layers. At 2115 LST, 4 hr. after sunset under broken cirrus, one would infer a surface inversion. At 1800 LST, Fort Worth was already reporting a 1.7°C. inversion from the surface to 200 m. A single ascent rate was maintained throughout the 2115 LST ascent.

In figure 3, the ascent at 1419 LST occurred with a trace of cloud at 4,000 ft. and broken cirrus. Both θ_{min} and the base of the inversion were at 1025 m. Again there is a pronounced inflection in the ascent curve with a much slower ascent rate through the upper half of the ascent. The balloon launched at 1953 LST $2\frac{1}{2}$ hr. after sunset under thin cirrus cloud, underwent an exceptionally uniform ascent. A surface inversion is inferred from the sky condition and time of day, although no inversion had formed by 1800 LST at Fort Worth.

The two ascents on November 23 in figure 4, show the same contrast. A balloon launched about $1\frac{1}{4}$ hr. after sunrise, with only scattered cirrus clouds, ascended at a uniform rate. A surface inversion was inferred from the the time of day and sky condition and from the observation 2 hr. earlier at Fort Worth of a 9.8°C. inversion from the surface to 230 m. Later that afternoon, with θ_{min} at 650 m. and the base of the inversion at 1375 m., the balloon ascended rapidly during the first 6 min. and then slowed noticeably.

At 1529 LST on November 18 a balloon was launched under a 5,000-ft. overcast. With θ_{min} at the surface there

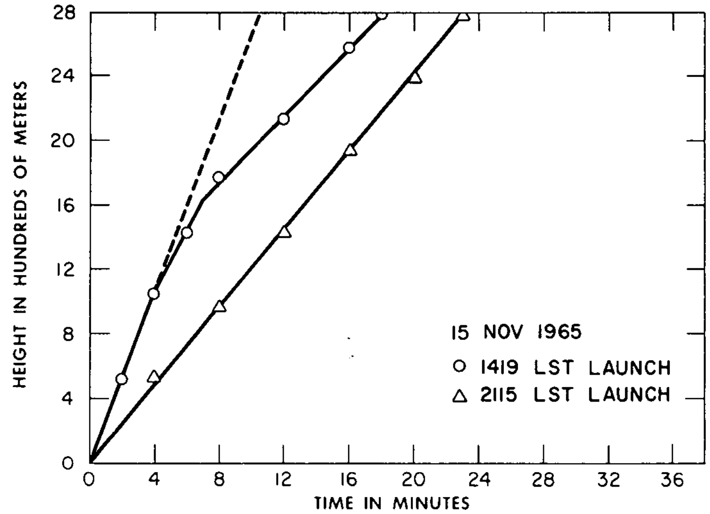

FIGURE 2.—Balloon height versus time, November 15, 1965. At 1419 LST, unstable to 1075 m., inversion 1525–1650 m.; at 2115 LST surface inversion.

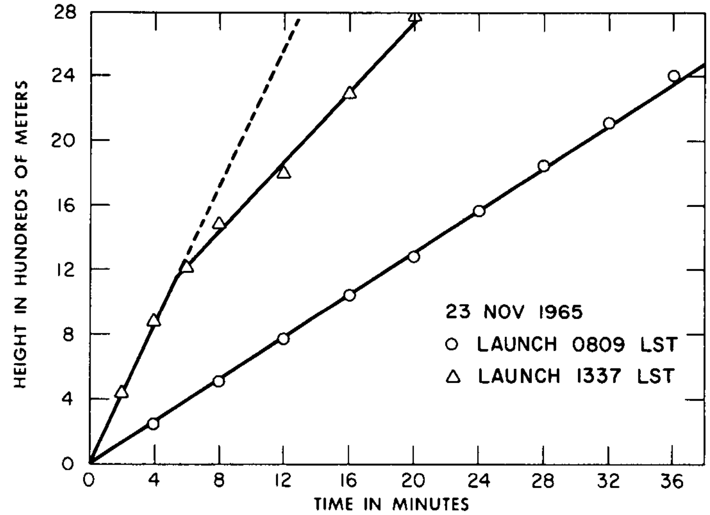

FIGURE 4.—Balloon height versus time, November 23, 1965. At 0809 LST, surface inversion; at 1337 LST, unstable to 650 m., inversion 1320–1490 m.

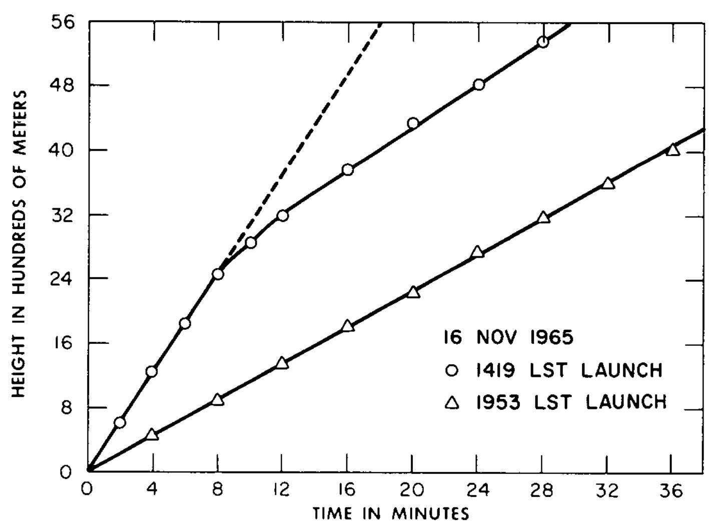

FIGURE 3.—Balloon height versus time, November 16, 1965. At 1419 LST, unstable to 1025 m., inversion 1025–1200 m.; at 1953 LST, surface inversion.

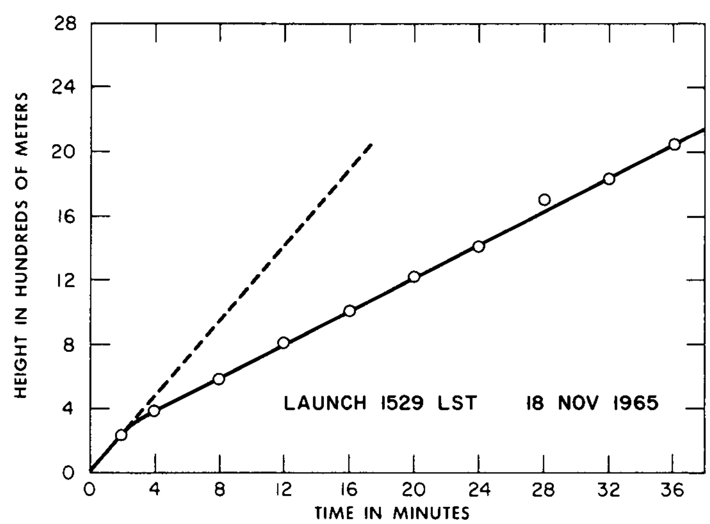

FIGURE 5.—Balloon height versus time, November 18, 1965. Stable from surface to inversion 1800–1925 m.

was no superadiabatic layer. The inversion was based at 1800 m. Figure 5 shows the time history of the ascent. Ascent is relatively uniform after the first 2 min. of more rapid ascent to 200 m.

If we consider uniform ascent as the normal or expected behavior we may summarize figures 2, 3, 4, and 5 as follows. A superadiabatic surface layer results in accelerated ascent through and sometimes for a short distance above the superadiabatic layer. A surface inversion does not alter the uniform ascent despite theoretical arguments that a deceleration ought to occur. The meaning of the shallow layer of rapid ascent in figure 5 is discussed later.

WIND PROFILE

Examples are presented for the superadiabatic case, the neutral case, and the inversion. Figures 6, 7, and 8 illustrate the variation of wind with height when there is a superadiabatic layer at the surface. On each figure the height of θ_{min} is seen to be in good agreement with the top of the mixed layer. The mixed layer is defined as the layer within which wind direction is uniform and the wind speed increases very little with height. Above the mixed layer the wind direction veers and the wind speed usually increases. The slight difference in indicated top of the mixed layer from the two profiles in figure 7 was typical of the present set of data. Figure 8 is an example of a wind speed that first decreases above the mixed layer and then increases rapidly. Clearly the top of the mixed layer as shown in figure 8 identifies the layer of uniform momentum. It may be noted that figure 4 depicts the balloon ascent that corresponds to the wind profiles of figure 7.

An example of profiles for the neutral case appears in figure 9. The balloon ascent for this flight, with θ_{min} at the surface, and inversion base at 1800 m., is shown in figure 5. The wind profiles suggest a shallow mixed layer of about 200 m. Rapid ascent through the lowest 200 m., noted in figure 5, is presumably associated with this mixing.

Two other examples of neutral profiles are given. At 0840 LST on November 13, a balloon was launched under a 200-ft. overcast that had been present for several hours. It is unlikely that a surface inversion would be present with this sky condition. The 0600 LST Fort Worth radiosonde showed a positive, stable lapse rate to 220 m. with an inversion from 220 to 600 m. The wind profiles shown in figure 10 suggest the presence of a mixed layer in the lowest 170 m. The early morning weather on November 20 was nearly identical. At 0600 LST Fort Worth showed a positive lapse rate to 130 m. with an inversion from 130 to 660 m. By 1040 LST, when the balloon was launched,

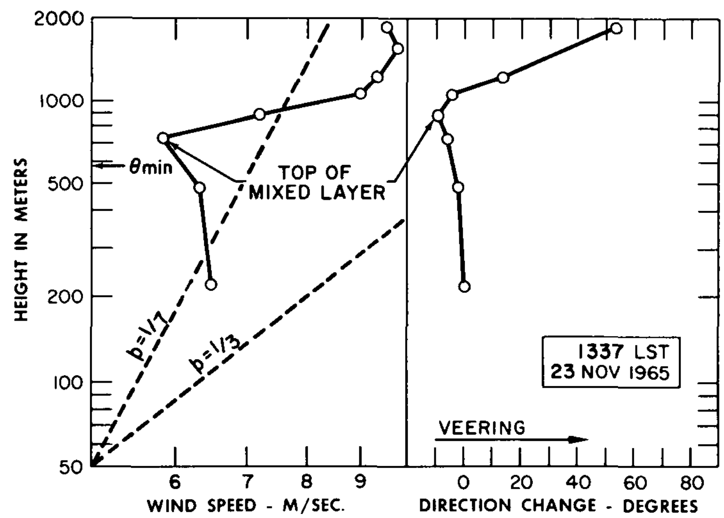

FIGURE 7.—Vertical profiles of wind speed and direction at Palestine, Texas, from rawin launched at 1337 LST, November 23, 1965. (Direction is plotted as change from the first measured wind.)

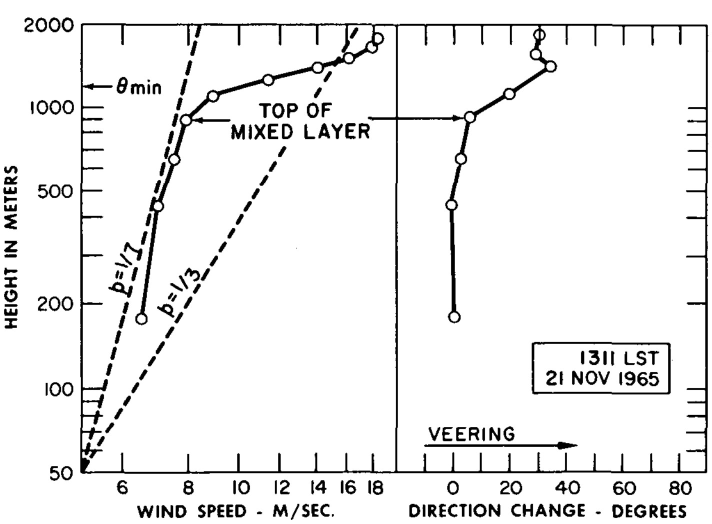

FIGURE 6.—Vertical profiles of wind speed and direction at Palestine, Texas, from rawin launched at 1311 LST, November 21, 1965. (Direction is plotted as change from the first measured wind.)

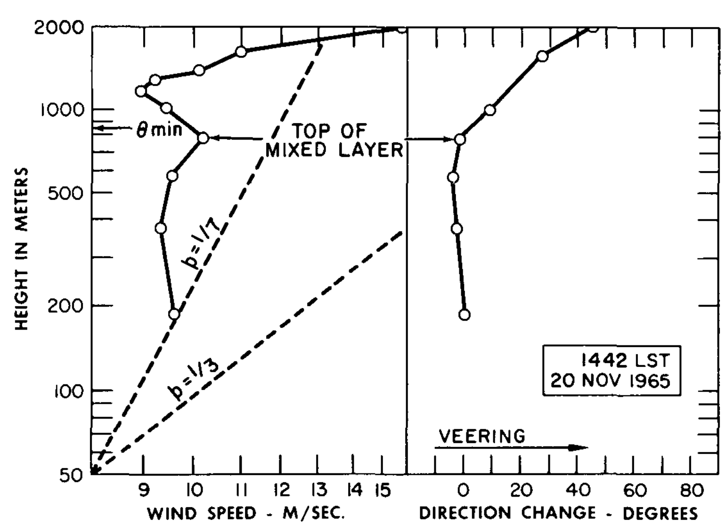

FIGURE 8.—Vertical profiles of wind speed and direction at Palestine, Texas, from rawin launched at 1442 LST, November 20, 1965. (Direction is plotted as change from the first measured wind.)

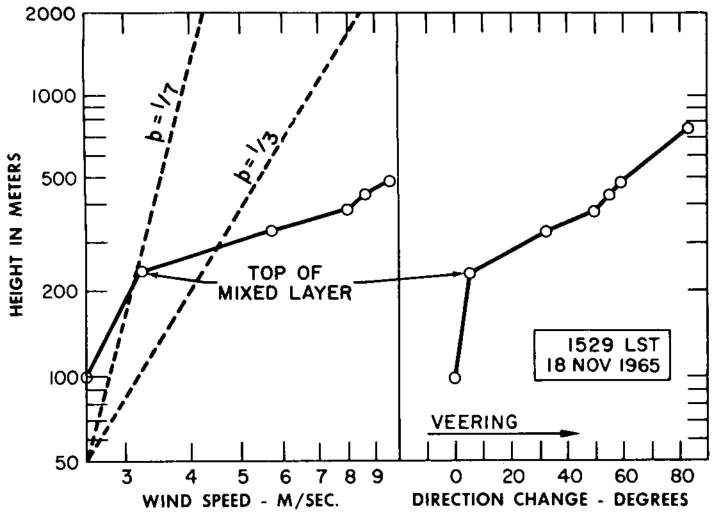

FIGURE 9.—Vertical profiles of wind speed and direction at Palestine, Texas, from rawin launched at 1529 LST, November 18, 1965. (Direction is plotted as change from the first measured wind.)

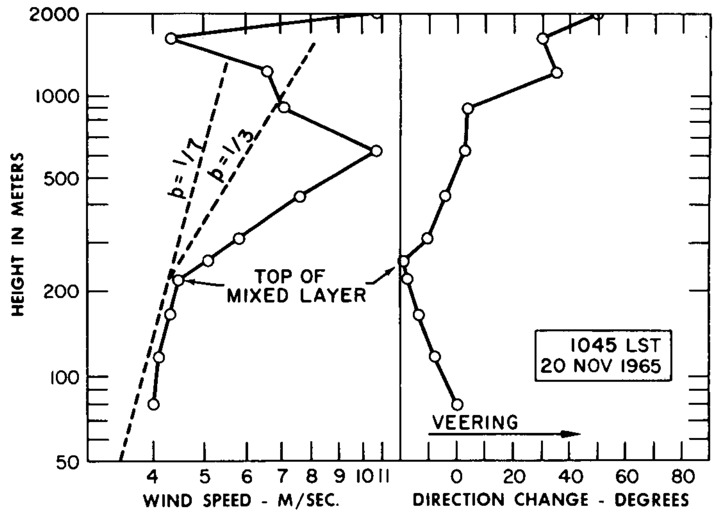

FIGURE 11.—Vertical profiles of wind speed and direction at Palestine, Texas, from rawin launched at 1045 LST, November 20, 1965. (Direction is plotted as change from the first measured wind.)

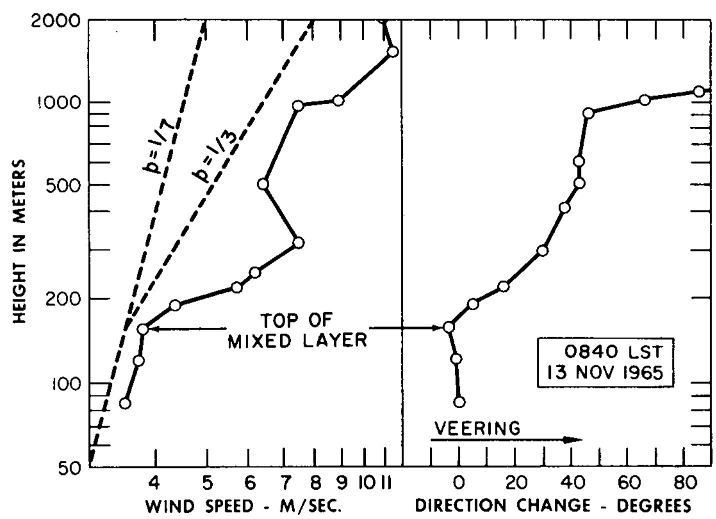

FIGURE 10.—Vertical profiles of wind speed and direction at Palestine, Texas, from rawin launched at 0840 LST, November 13, 1965. (Direction is plotted as change from the first measured wind.)

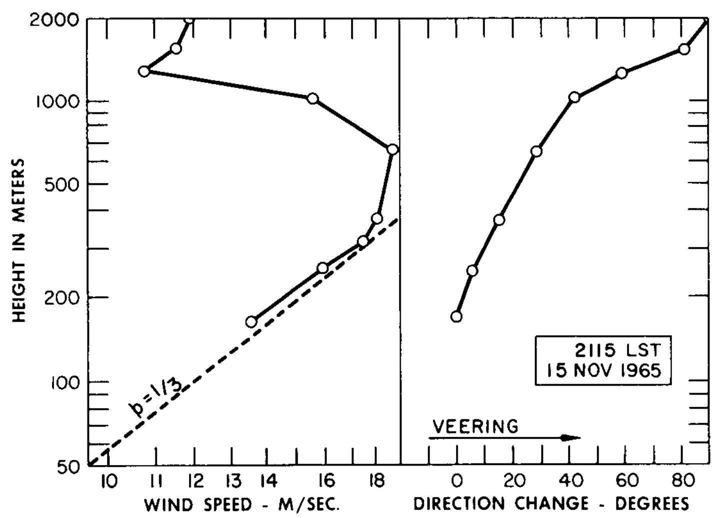

FIGURE 12.—Vertical profiles of wind speed and direction at Palestine, Texas, from rawin launched at 2115 LST, November 15, 1965. (Direction is plotted as change from the first measured wind.)

only a few fractostratus remained below a 5,000-ft. overcast. Figure 11 shows a mixed layer a little over 200 m. deep.

In figure 2 the ascent at 2115 LST nearly 4 hr. after sunset, was given as an inversion example. Figure 12 shows the wind profiles observed during the same ascent. The wind increases rapidly in speed and veers from the lowest level indicating that no mixed layer exists. The low-level jet, a co-feature of nocturnal inversions on the Dallas tower [4, 5, 6, 12] is already in evidence. Figure 13 is an example of wind profiles at dawn. At 0600 LST, Fort Worth showed on 8.5°C. inversion from the surface to 350 m. The low-level jet is again in evidence without any trace of a mixed layer in either the speed or direction plots. The corresponding balloon-ascent curve is shown in figure 14. Although it is slightly curved, it lacks the inflection that characterized ascents where the surface layer was well mixed.

Collectively the wind profiles suggest that the presence of a well-mixed surface layer is manifested by uniform wind direction and very little increase in speed. Above the mixed layer wind direction veers and wind speed increases at a rate corresponding to $p \geqq 1/3$. When the mixing is caused by convection the top of the mixed layer is in fair agreement with the height of the minimum potential temperature.

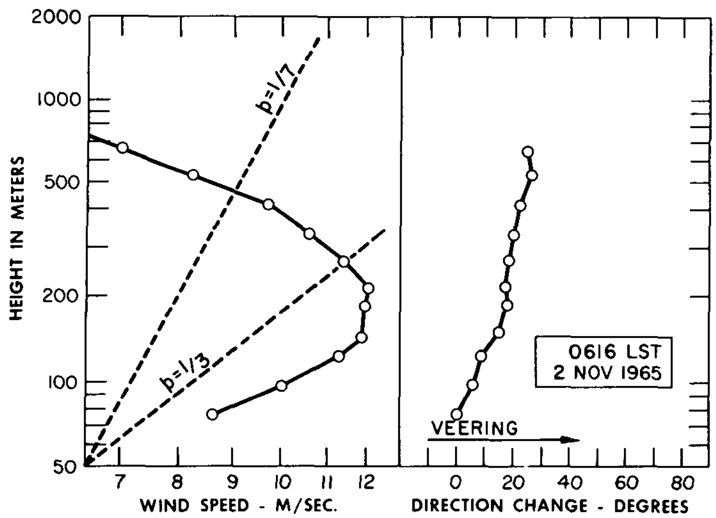

FIGURE 13.—Vertical profiles of wind speed and direction at Palestine, Texas, from rawin launched at 0616 LST, November 2, 1965. (Direction is plotted as change from the first measured wind.)

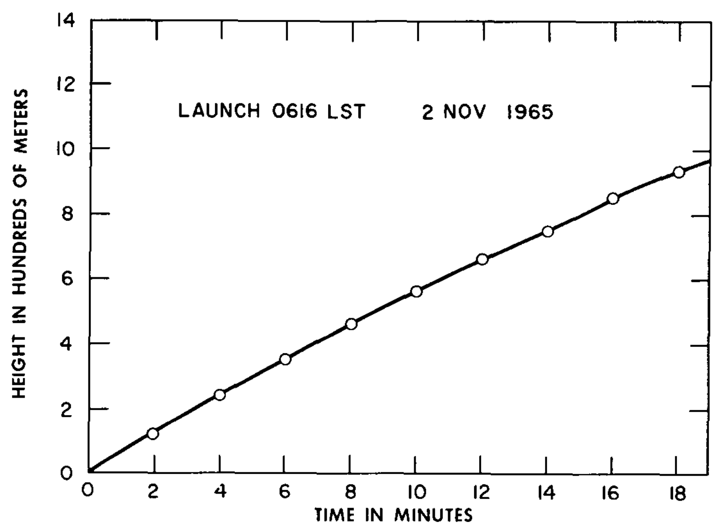

FIGURE 14.—Balloon height versus time, during surface inversion, November 2, 1965.

VERTICAL WIND COMPONENT

It should be recalled that the method of computing vertical wind components assumed that the mean rate of ascent for the entire flight was a good estimate of the still-air rate of ascent. For a flight such as the 1419 LST launch on November 16 (see fig. 3), there are systematic errors in such an assumption. Consequently only a few general comments are justified.

Flights conducted when superadiabatic conditions were observed generally gave vertical components numerically larger than 0.8 m. sec.$^{-1}$ Frequently they remained as large well above the top of the adiabatic layer suggesting that a convective cell may deflect a more or less laminar flow at much higher levels. Flights conducted when inversions were believed to be present gave vertical components less

TABLE 1.—*Summary of the relationship between stability in the surface layer and data extracted from tracking a rising balloon*

	Ascent rate	V vs z	DD vs z	Magnitude of vertical wind component (m./sec.)
Inversion	uniform	$p \geqq 1/3$	veers	$\leqq 0.3$
Neutral	slows above inflection	$1/7 < p < 1/3$	uniform	< 0.8
Superadiabatic	slows above inflection	$p \leqq 1/7$	uniform	$\geqq 0.8$

than 0.3 m. sec.$^{-1}$ and frequently no more than 0.1 m. sec.$^{-1}$ Flights conducted during positive but stable lapse rates occasionally gave vertical components as large as 0.8 m. sec.$^{-1}$ throughout the ascent. They appeared to be associated with wave formations whose wavelength was a few kilometers. At other times the vertical components were as small as those noted during inversions.

4. CONCLUSIONS

Local or regional effects that may have influenced the findings are the heavily treed and gently rolling terrain, the low-level jet, which is endemic to this area, and the persistent inversion aloft. Confirmation of the results in mid-summer, in the interior of the continent is needed. With the above reservations, the conclusions warranted by this study are summarized in table 1.

Table 1 shows that an inversion can be unambiguously inferred. The difference between the neutral and superadiabatic cases is subtle and mainly a matter of the depth of the mixed layer. Hence such factors as time of day, sky condition, and weather should temper the application of table 1. For example superadiabatic conditions are a possibility during midday, under sunny skies. The conditions would be confirmed if the features shown in line 3 of table 1 were observed and the depth of the mixed layer were several hundred meters. Conversely if one were to observe quite similar features at night or under overcast skies, except that the mixed layer were only a few hundred meters deep, one should infer a neutral lapse rate. It is apparent that mechanical turbulence is sometimes able to maintain a shallow mixed layer.

Presumably multiple-theodolite tracking of balloons would give similar results. Triple-theodolite pibals were reported by Rider and Armendariz [8] to give profiles that had the same shape as those obtained from tower wind measurements.

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